CRUDE OIL, CLIMATE CHANGE, COAL, CANE AND CARS

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CLIMATE CHANGE
CRUDE OIL
COAL
?
CARS
SUGAR CANE

CLIMATE CHANGE

CRUDE OIL

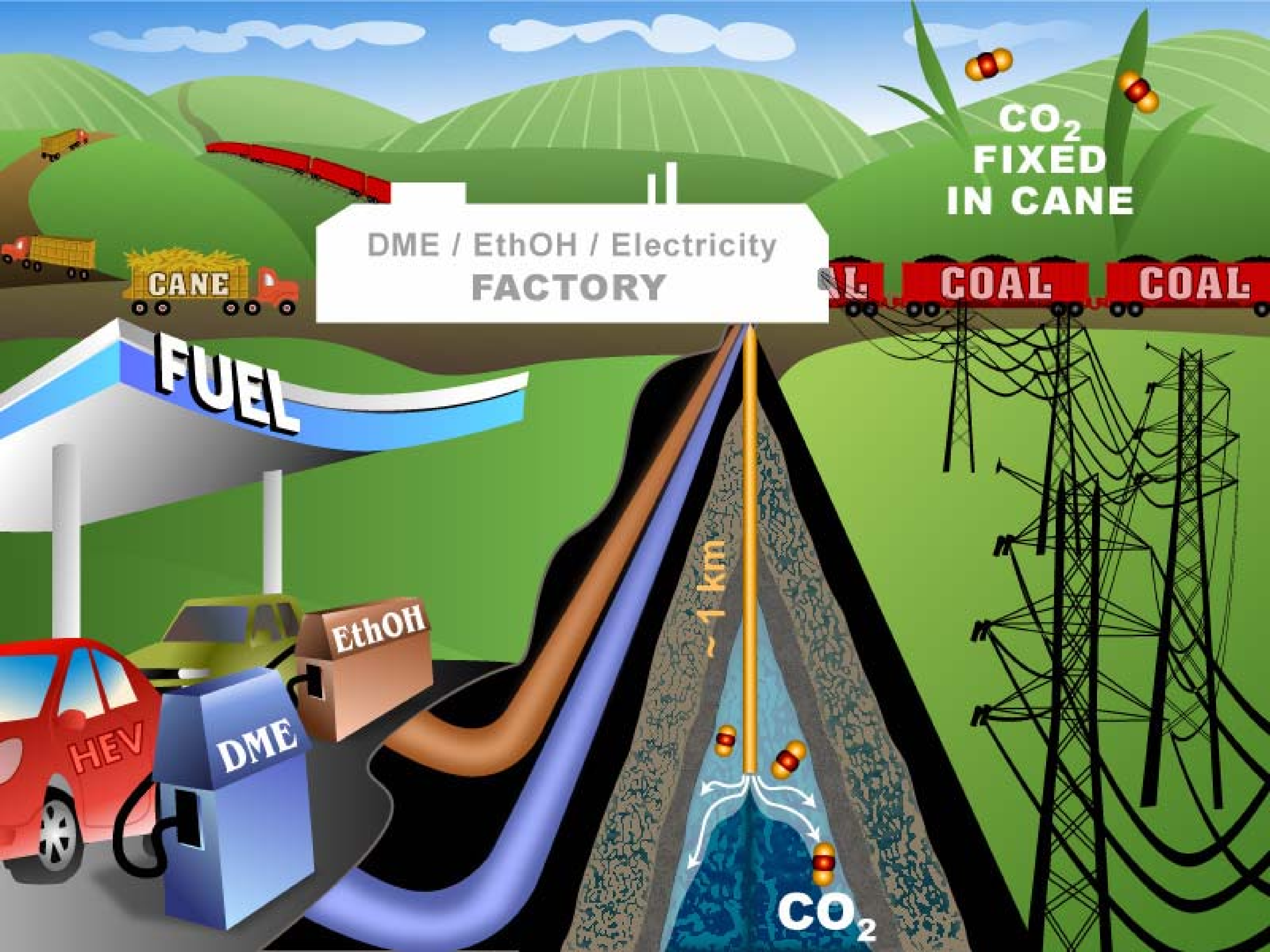
COAL

Solving climate/oil problems posed by cars requires radical energy system change…needed technology is within reach…but there are major cultural-institutional challenges

EXPLORING SOME OPTIONS FOR THIS QTR CENTURY

CARS

SUGAR CANE



CO$_2$ FIXED IN CANE
DME / EthOH / Electricity
FACTORY
CANE
COAL
COAL
FUEL
~1 km
EthOH
DME
HEV
CO$_2$

MAJOR CHALLENGES POSED BY OIL AND CARS

- Supply insecurity
- Oil price (*prospective peaking of global production*)
- Health impacts of air pollution (*especially for Diesel vehicles*)
- Climate change (*need to decarbonize energy for cars*)

THE CAR'S CONTRIBUTION TO OIL, CLIMATE CHALLENGES

Year	2000	2030
Number of light-duty vehicles worldwide, 10^6	690	1270
Average fuel economy (mpg_{ge})	*24.4*	*28.0*
Oil required, 10^6 barrels/day (% of Persian Gulf production, 2000)	16.7 (*89*)	27.1 (*136*)
Fuel cycle-wide GHG emissions, GtC/year (% of global total, 2000)	0.74 (*11.6*)	1.20 (*18.8*)

Source: World Business Council for Sustainable Development, *Mobility 2030: Meeting the Challenges of Sustainability*, The Sustainable Mobility Project, 2004

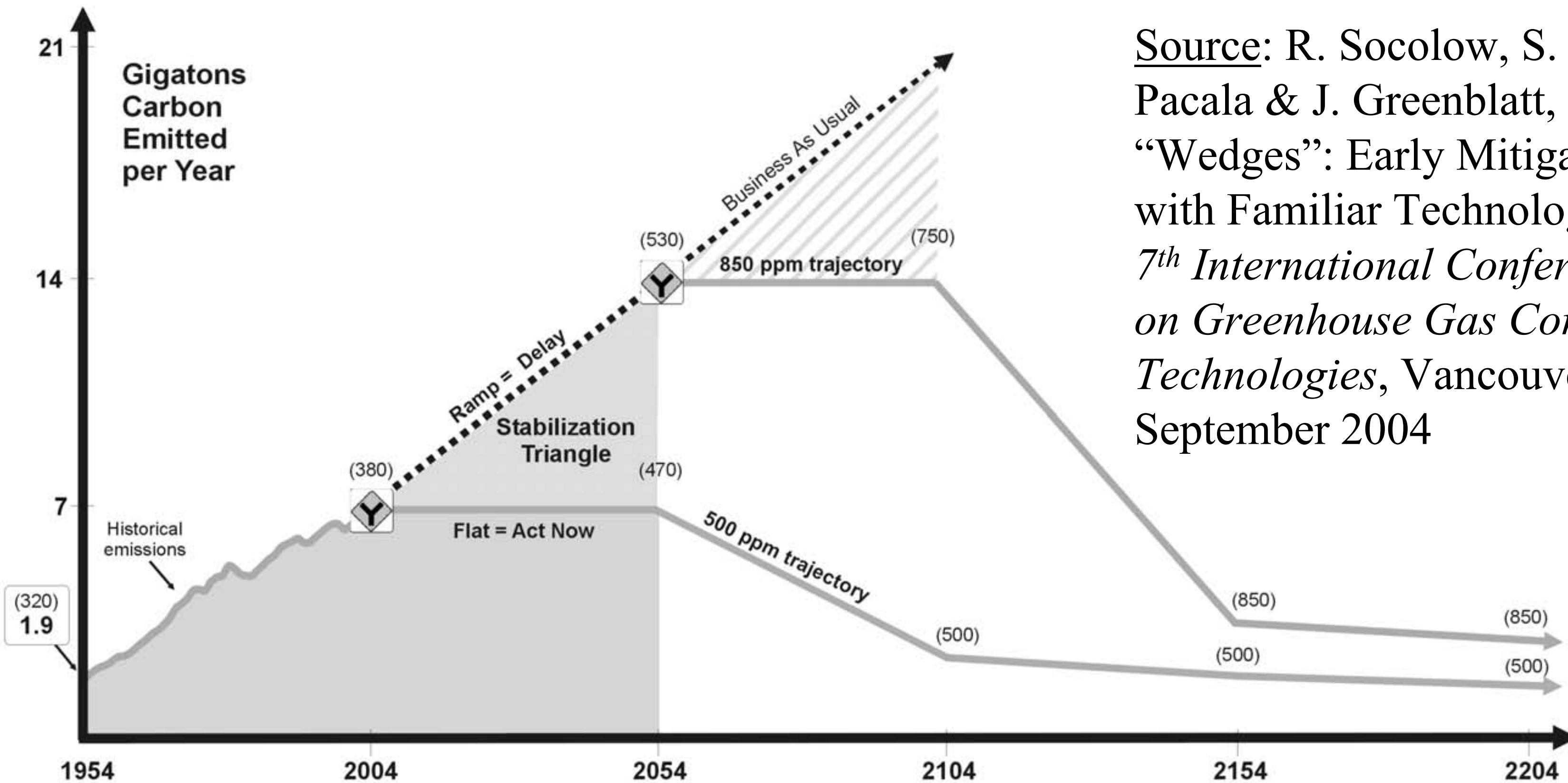
Growing Middle East tensions plus constraints on world oil production

DATE OF WORLD OIL PRODUCTION PEAK

Alternative estimates of ultimately recoverable conventional oil (*10^9 barrels*)	1800	2400	3000
Peak year with no unconventional oil	2001	2012	2021
Peak year if GTL is only unconventional oil (*360 x10^9 barrels from 2000 TCF NG*)	2008	2017	2025
Peak year if Canadian tar sands also included (*300 out of 1700 x 10^9 barrels OOIP*)	2013	2021	2028
Peak year if Venezuelan heavy oil also included (*272 out of 1200 x 10^9 barrels OOIP*)	2017	2025	2032

Without expansion of Middle East capacity, peak would occur earlier

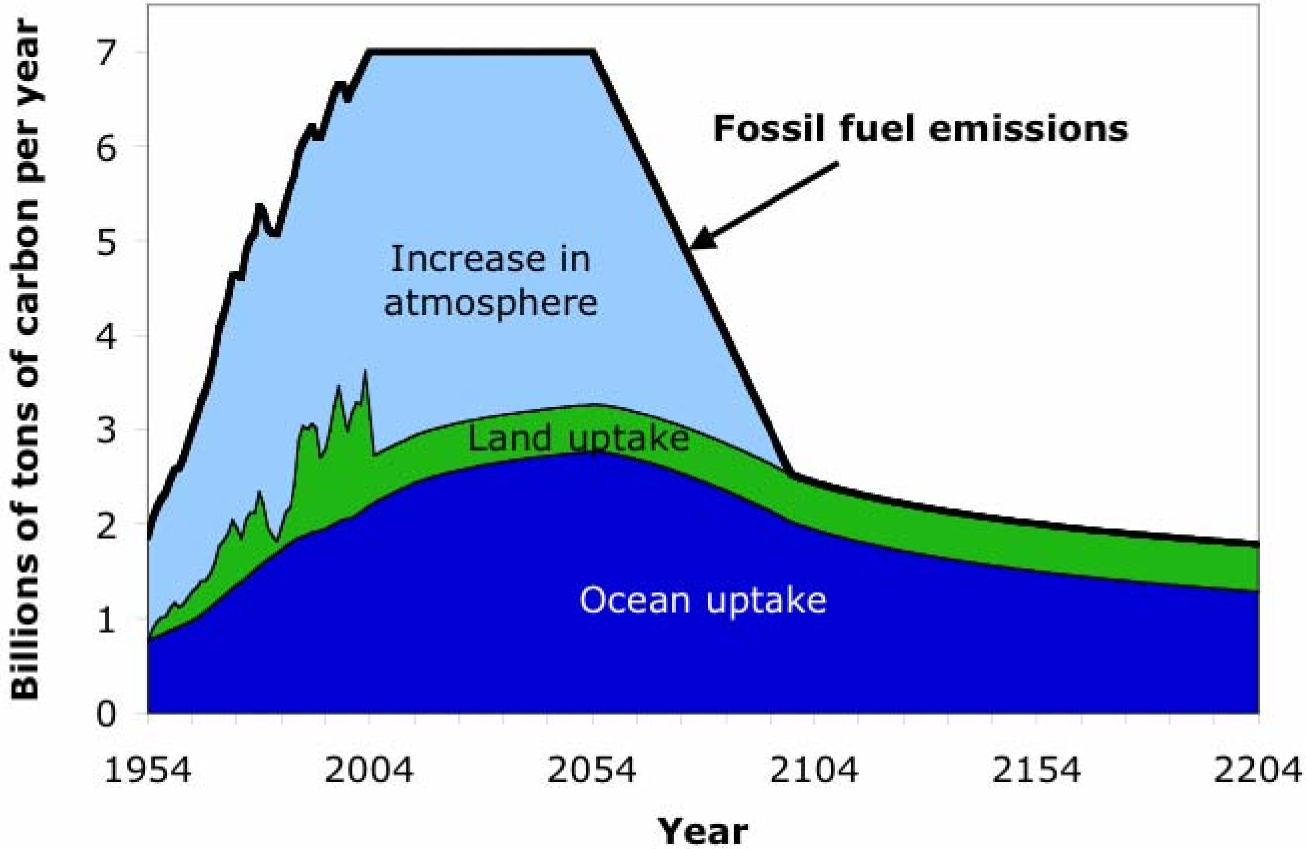
WHAT IS REQUIRED TO STABILIZE ATMOSPHERIC CO_2 AT ≤ 2X PRE-INDUSTRIAL LEVEL



Source: R. Socolow, S. Pacala & J. Greenblatt, "Wedges": Early Mitigation with Familiar Technology," *7th International Conference on Greenhouse Gas Control Technologies*, Vancouver, September 2004

Stabilizing @ 500 ppm CO_2 ➔ cut emissions ~ 7 GtC/y relative to BAU by 2050

EMISSIONS IN RELATION TO SINKS FOR STABILIZATION TRAJECTORY



Source: R. Socolow, R. Hotinski, J.B. Greenblatt, and S. Pacala, 2004: Solving the climate problem: technologies available to curb CO_2 emissions, *Environment*, December (in press).

Distribution of Global CO_2 Emissions from FFs (%)

Year	2000	2020	2050
Electricity generation	36	25-38	22-43
Industry	32	28-32	24-37
Transportation	21	21-25	18-33
Residential/commercial	12	12-20	11-19

Must decarbonize fuels used directly (FUD) as well as electricity

IEA data for 2000. Projections are for A1B-AIM, AIT-Message, A2-Image, B1-Image, B2-Message scenarios of IPCC's *Special Report on Emissions Scenarios* (IPCC, 2000)

IS IT FEASIBLE TO STABILIZE ATMOSPHERIC CO_2 AT 500 ppmv?

- Daunting challenge—no silver bullet
- But lots of "lead bullets" based on commercial or near commercial technologies…each of which could plausibly contribute ~ 1 GtC/y emissions reduction by 2050:
  - Panopoly of opportunities for improving energy end-use technology
  - Fuel shifting to less carbon-intensive natural gas
  - Various renewables
  - Fossil fuel decarbonization via CO_2 capture and storage (*CCS*)
- Decarbonizing "fuels used directly" is generally thought to be much harder than decarbonizing electricity
  - Hydrogen economy is most discussed option…but is a long way off
  - Will decribe a plausible alternative option that can have significant impact in this quarter century
- Radical technology (*e.g., artificial photosynthesis*) needed for second half of century

OUTLOOK FOR AUTO FUEL ECONOMY

	Current technology	Advanced technology *(~ 2020)*	
Engine (E) type:	SIE	SIE/HE	CIE/HE
Power/weight (*kW/t*)	75	75	75
Fuel economy (mpg_{ge})	30	69	80
Weight (t) (*w/136 kg payload*)	1.46	1.16	1.19
Drag coefficient	0.33	0.22	0.22
Frontal area (*m^2*)	2.0	1.8	1.8
Rolling resistance	0.009	0.006	0.006
Auxiliary power (*kW*)	0.7	1.0	1.0

Source: M.A. Weiss, J.B. Heywood, A. Schafer, and V.K. Natarajan, *Comparative Assessment of Fuel Cell Cars*, MIT LFEE 2003-001 RP, February 2003

By 2020, new CIE/HE cars could be (80/30) = 2.7 X as fuel-efficient as today's gasoline cars without loss of performance ➔ 65 mpg_{ge}. "Designer" synfuels could facilitate transition to CIE/HE cars

SIE/CIE = spark-ignition engine/compression-ignition engine; HE = hybrid-electric

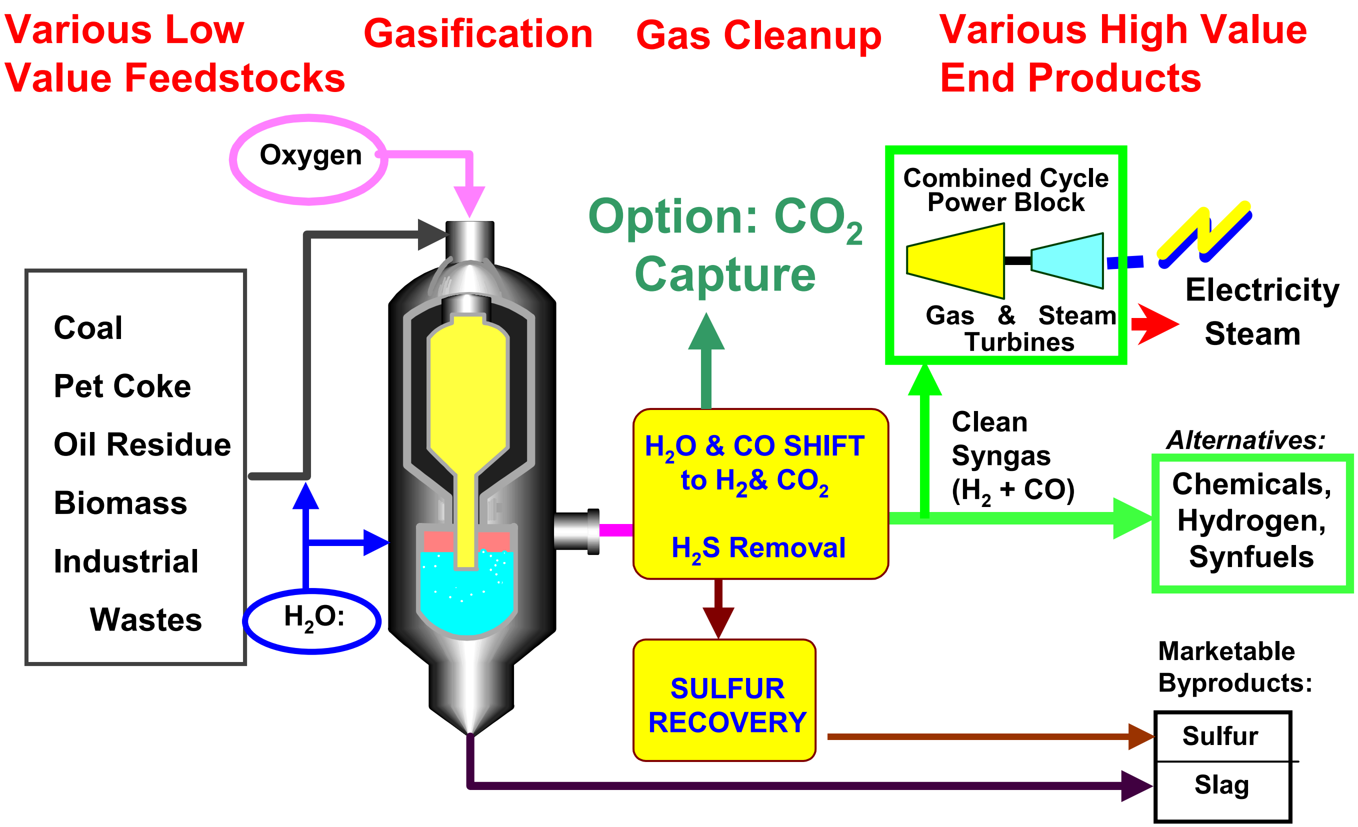
COAL: CHALLENGE…AND OPPORTUNITY

- Coal = main challenge for energy w/r to climate change
- Also severe air pollution problems, mining hazards
- Coal not likely to be abandoned because of:
  - Coal abundance
  - Low, non-volatile coal prices
- Can coal be made environmentally acceptable? Gasification is key:
  - Gasification can make coal electricity as clean as NGCC power
  - Coal synfuels (*via gasification*) can be cleaner that crude oil-derived HC fuels
  - Pre-combustion CCS via gasification: least costly way to decarbonize coal
  - Coal synfuels made with CCS ➔ slightly less GHG emissions than for crude oil-derived HC fuels…not good enough for CO_2 stabilization at 500 ppmv
  - Synfuels from biomass/coal with CCS: promising route to low GHG emissions

WHY SYNFUELS FROM COAL AND BIOMASS?

- Constraints on conventional oil, most other unconventional oil sources
- Gasification-based coal synfuels are nearly commercially ready...and competitive at oil prices less than $35 per barrel
- China is intent on pursuing coal-derived liquid fuels
- Fuels from biomass and coal with CO_2 capture and storage (CCS) makes it feasible to deal effectively with the climate challenge
- Alternative options for decarbonizing transport fuels have limited potential for addressing climate challenge in this Qtr century:
  - H_2 fuel cell vehicles (*R&D focus of many major automakers*) cannot make major contributions until 2^{nd} Qtr of 21^{st} century
  - Land-use constraints ➔ biofuels *alone* cannot do the job
- Foci of talk:
  - Synfuels with capture and underground storage of CO_2
  - Coal/biomass, including coprocessing (*emphasis on sugar cane*)
  - Designer" synfuels that can facilitate shift to super-energy-efficient hybrid-electric cars

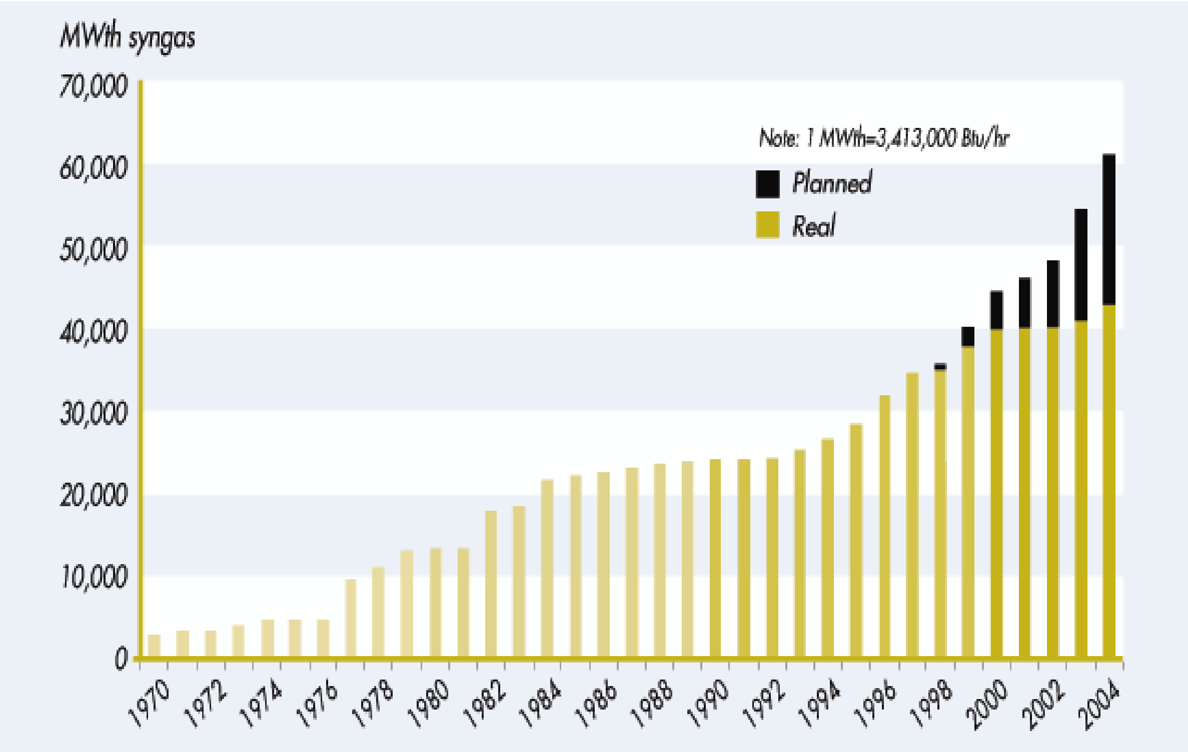
GASIFICATION TO CONVERT LOW-VALUE FEEDSTOCKS INTO HIGH-VALUE PRODUCTS



WGS ($CO + H_2O \rightarrow H_2 + CO_2$) is key both to creation of high-value products and to decarbonization for climate-change mitigation

Coal must be focus of CO_2 capture and storage effort

GASIFICATION IS BOOMING GLOBAL ACTIVITY



Worldwide gasification capacity is increasing by 3 GW_{th} per year and will reach 61 GW_{th} in 2004

- **In 2004**
- By activity:
- 24 GW_{th} chemicals
- 23 GW_{th} power
- 14 GW_{th} synfuels
- By region:
- 9 GW_{th} China
- 10 GW_{th} N America
- 19 GW_{th} W Europe
- 23 GW_{th} Rest of world

By feedstock:

- 27 GW_{th} petroleum residuals
- 27 GW_{th} coal
- 6 GW_{th} natural gas
- 1 GW_{th} biomass

Current market dominated by polygeneration of chemicals, electricity, process heat via petroleum residuals gasification…largest potential = polygeneration of synfuels, electricity, processs heat via coal gasification

OPTIONS FOR CO_2 DISPOSAL

- Goal: store 100s to 1000s of GtC for long periods (*100s to 1000s of y*)
- Major options, disposal in:
  - Deep ocean (*concerns about storage effectiveness, environmental impacts, legal issues, difficult access*)
  - Carbonate rocks [*100% safe, costly (huge rock volumes), embryonic*]
  - Disposal in geological media (*focus of current interest*)
    - Enhanced oil recovery (*30 million tonnes CO_2/y—4% of US oil production*)
    - Depleted oil and gas fields (*geographically limited*)
    - Beds of unminable coal (*CO_2 adsorbed in pore spaces of coal*)
    - Deep saline aquifers—huge potential, ubiquitous (*at least 800 m down*)
      - Such aquifers underly land area = ½ area of inhabited continents (*2/3 onshore, 1/3 offshore*)
  - Most large anthropogenic CO_2 sources within 0-200 km of geological disposal sites (*800 km = longest US CO_2 pipeline for EOR*)
  - Already some experience (*e.g., Sleipner, North Sea; EOR*) but many more "megascale" CO_2 storage demos needed

MAKING LIQUID FUELS FROM COAL

- Gasify coal in O_2/H_2O to produce "syngas" (*mostly* CO, H_2)
- <u>Challenge</u>: increase H/C ratio to ~ 2 to 4 (*H/C ~ 0.8 for coal*)
- Increase H/C ratio via water gas shift reaction ($CO + H_2O \rightarrow H_2 + CO_2$) to maximize conversion in synthesis reactor
- Remove acid gases (H_2S *and* CO_2), other impurities from syngas
- Convert syngas to liquid fuel in "synthesis" reactor

SYNFUEL OPTIONS VIA COAL GASIFICATION

F-T Diesel
- → Blend with crude oil-derived Diesel
- → Use as substitute for crude oil-derived Diesel

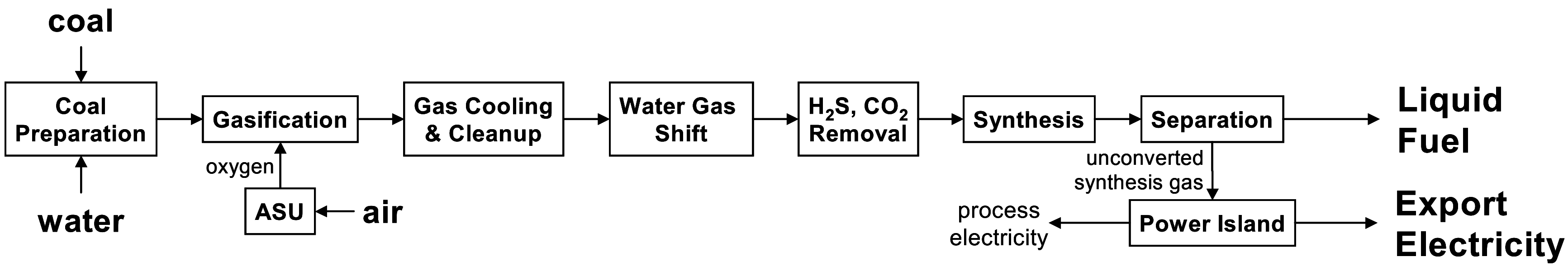
MeOH
- → Convert to gasoline (*Mobil process*)
- → Use directly as fuel
- → Convert to DME via dehydration

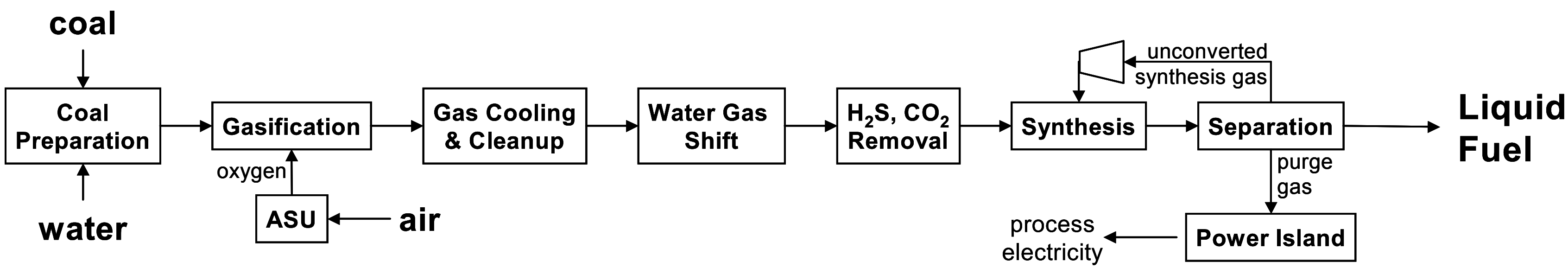
DME → Use directly as fuel

CANDIDATE DESIGNER FUEL: DME (CH_3OCH_3)

- Ozone-safe aerosol propellant and chemical feedstock
- Production ~ 150,000 t/y by MeOH dehydration (*small plants*)
- Prospective clean cooking fuel—LPG supplement—esp. for LDCs
- Prospectively outstanding compression-ignition engine (*CIE*) fuel:
  - high cetane #
  - no sulfur, no C-C bonds that could lead to soot ➔ no PM/NO_x tradeoff in quest for low emissions, so low NO_x emission rate readily achievable
- Drawbacks:
  - Gas at atmospheric pressure—mild pressurization (*as for LPG*) needed ➔ need new infrastructure for transport applications
  - Further engine developments needed before DME is ready for transport markets
- Production plans:
  - NG → DME: 110,000 t/y (*Sichuan, China, 2005*); 800,000 t/y (*Iran, 2006*)
  - Coal → DME (*800,000 t/y project approved, Ningxia, China*)

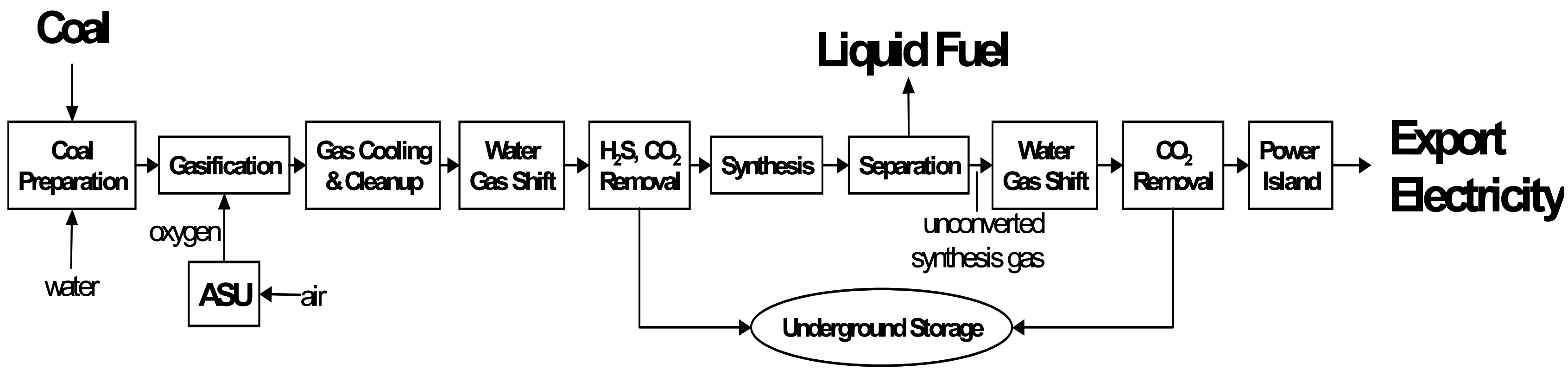
ONCE-THROUGH (OT) vs RECYLE (RC) OPTIONS





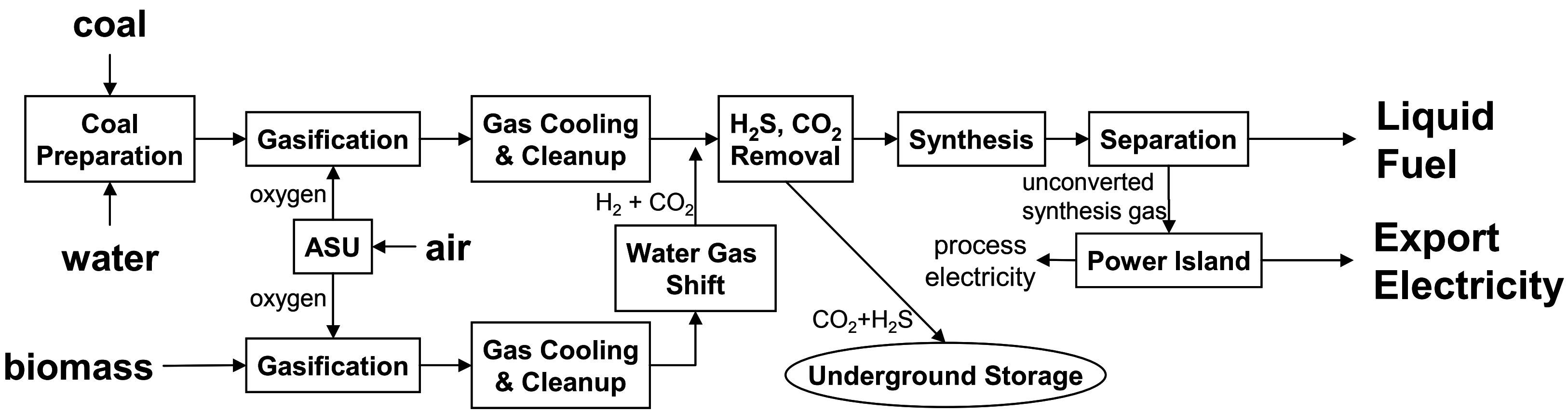
- <u>OT option</u> (*top*): syngas passes once through synthesis reactor; unconverted syngas burned → electricity coproduct in combined cycle
- <u>RC option</u> (*bottom*): unconverted syngas recycled to maximize synfuel production; purge gases burned → electricity only for process; no electricity for export
- OT systems are often the most cost-effective using new liquid-phase synthesis reactors…if markets are available for electricity coproduct

Under Climate Constraint, Coproduce Liquid Fuel + Electricity with CO_2 Capture Upstream and Downstream of Synthesis Reactor



Fuel-cycle-wide GHG emissions for coal-derived liquid fuels can be 80-90% of emissions for crude-oil-derived hydrocarbon fuels with CCS…but must do much better under C constraint

COPROCESSING BIOMASS WITH COAL TO MAKE LIQUID FUELS PLUS ELECTRICITY



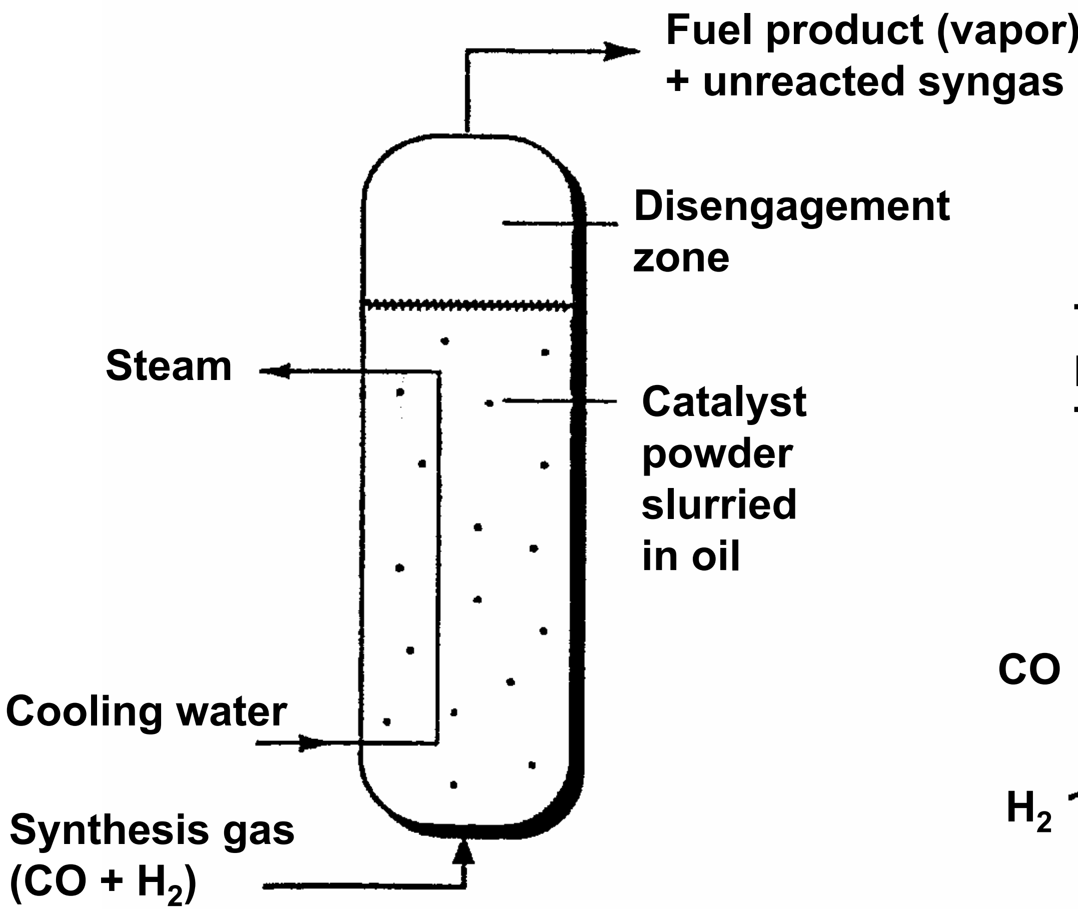
Alternative to shifting coal syngas to achieve desired H_2/CO ratio for synthesis: provide H_2 from biomass via gasification & store CO_2 coproduct underground ➔ "negative" CO_2 emissions for biomass will partially offset CO_2 emissions from synfuel combustion

➔synfuels with low net CO_2 emissions using much less land than for "pure" biofuels…and economic gain under carbon contraint

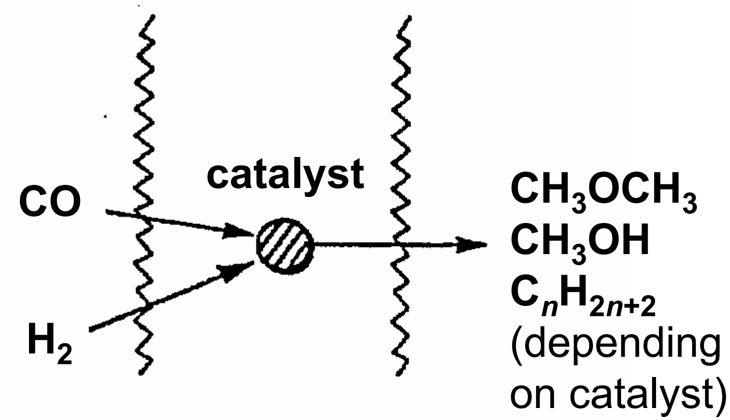
Liquid-Phase (LP) Synthesis Technology

Well-suited for use with
CO-rich (coal-derived) syngas

Liquid-phase reactors have much higher one-pass conversion of $CO+H_2$ to liquids than traditional gas-phase reactors, e.g., liquid-phase Fischer-Tropsch synthesis has ~80% one-pass conversion, compared to <40% for traditional technology.



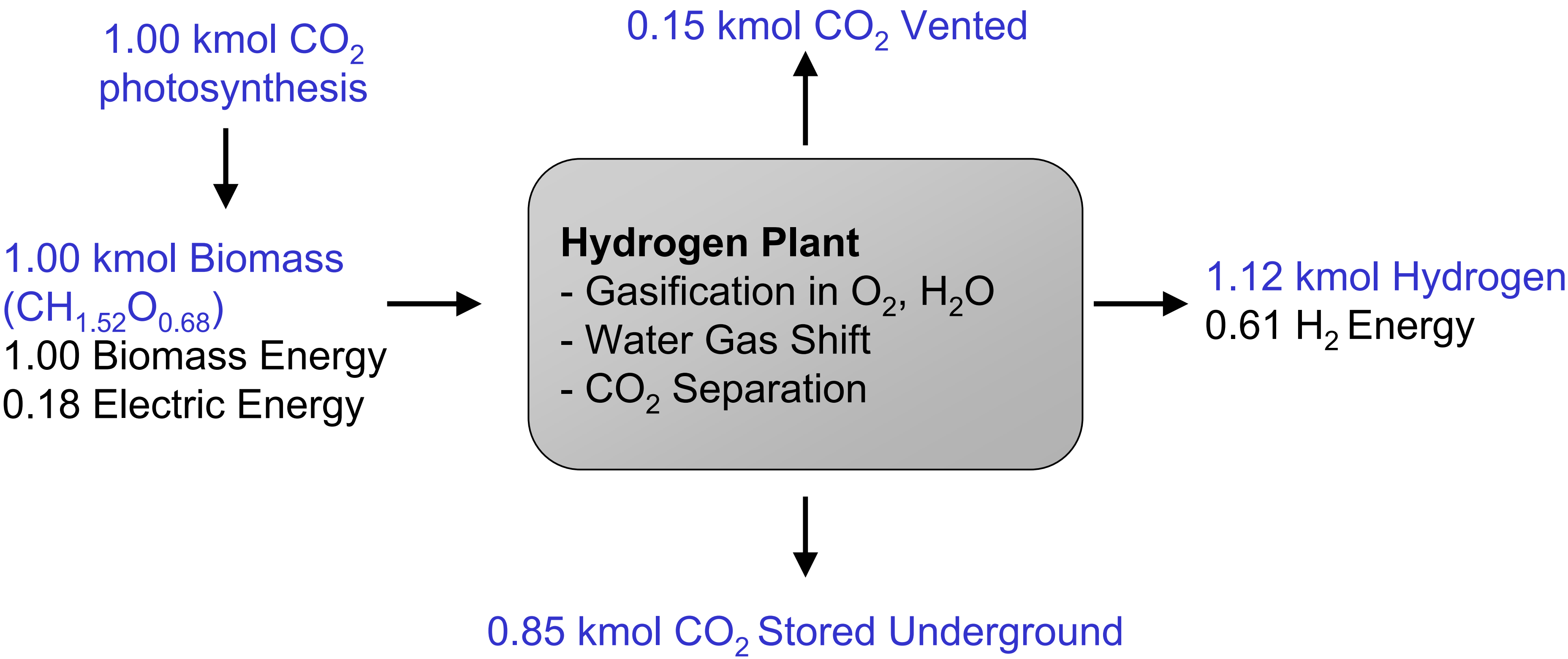
TYPICAL REACTION CONDITIONS:
P = 50-100 atmospheres
T = 200-300°C



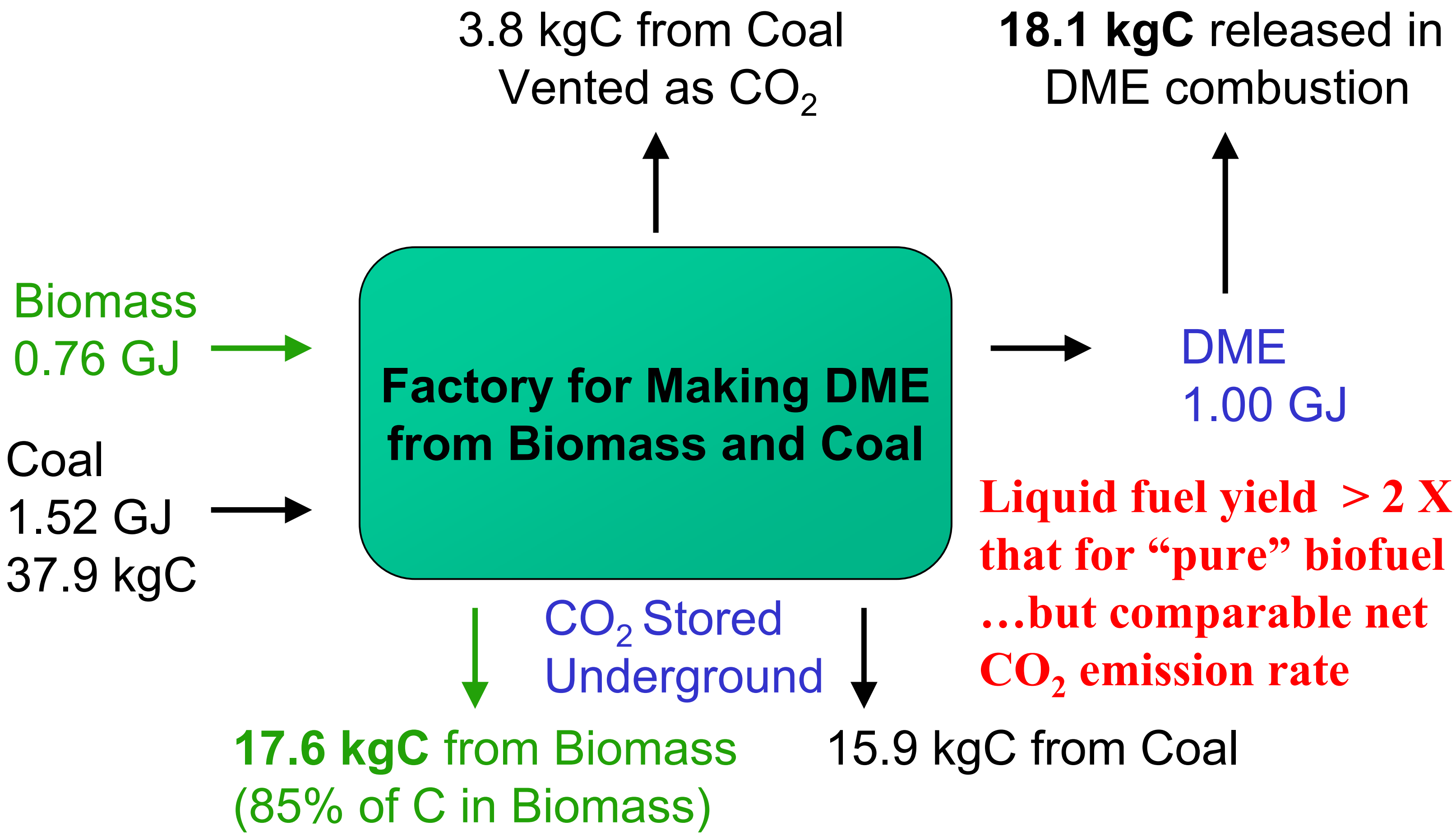
Status of LP Synthesis Technology

	Fischer-Tropsch	MeOH	DME
Commercial units in operation	✓		
Demonstrated at commercial scale		✓	
Demonstrated at pilot-plant scale			✓

POTENTIAL FOR NEGATIVE CO_2 EMISSIONS VIA BIOMASS H_2 WITH CCS

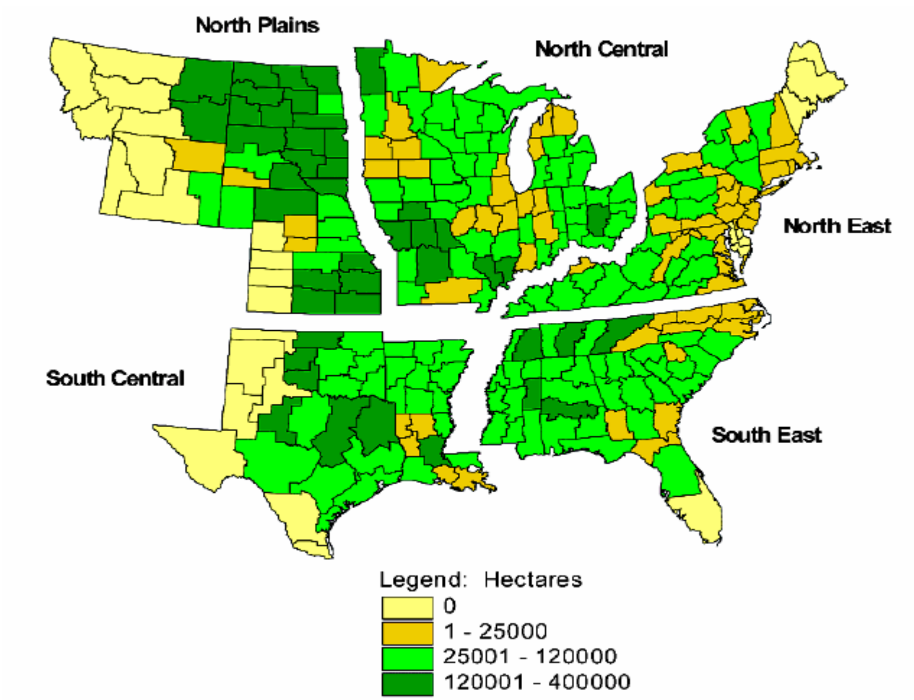


ENERGY/CARBON BALANCES FOR PLANT MAKING DME FROM COAL/BIOMASS WITH ULTRA-LOW NET SYSTEM-WIDE CO_2 EMISSIONS



BIOMASS FEEDSTOCK OPTIONS

- Agricultural/forest product industry residues in near term
  - DME from pulp and paper residues (*Sweden*)
  - Sugar cane in developing countries (*esp. Brazil*)
- Energy crops—e.g., switchgrass in Great Plains—longer-term



Source: McLaughlin et al., 2002: High-value renewable energy from prairie grasses, *Envir. Sci.& Tech.*, **36** (10): 2122-2129

Projected production density based on distribution of land that converts from conventional agriculture to switchgrass at a farm-gate price of \$44/t

WHY SUGAR CANE?

- Well-established industry
  - *~ 20 million hectares established worldwide*
  - *Cane production growing 2%/y worldwide*

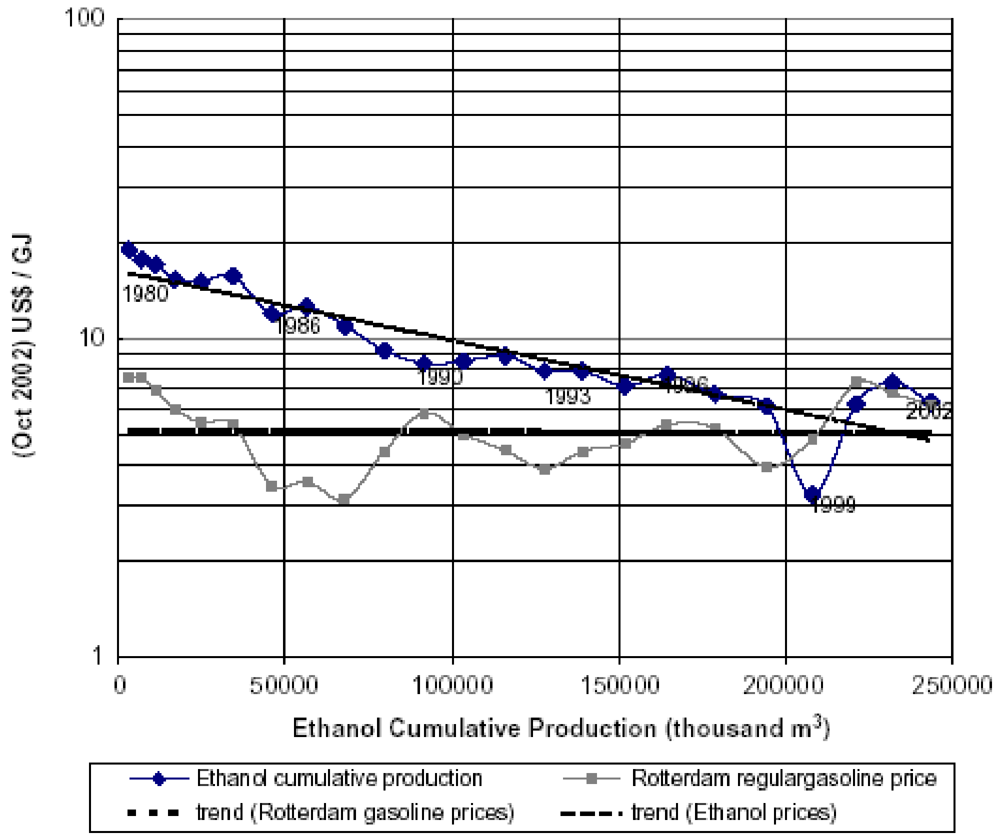
- High photosynthetic efficiency: average recoverable dry plant matter:
  - 10.1 t/ha/y sugar (*bagasse-equivalent*)
  - 13.6 t/ha/y recoverable residues [*bagasse + 60% of "barbojo"* (*tops/leaves*)]

- In Brazil, EthOH from sugar cane produced, without subsidy, at price competitive with crude oil-derived gasoline at 2002 world oil price (*$24/barrel*)

- Sugar in cane is converted efficiently ($\eta \sim 75\%$) to EthOH…but sugar is only ~ 40% of energy content of recoverable cane

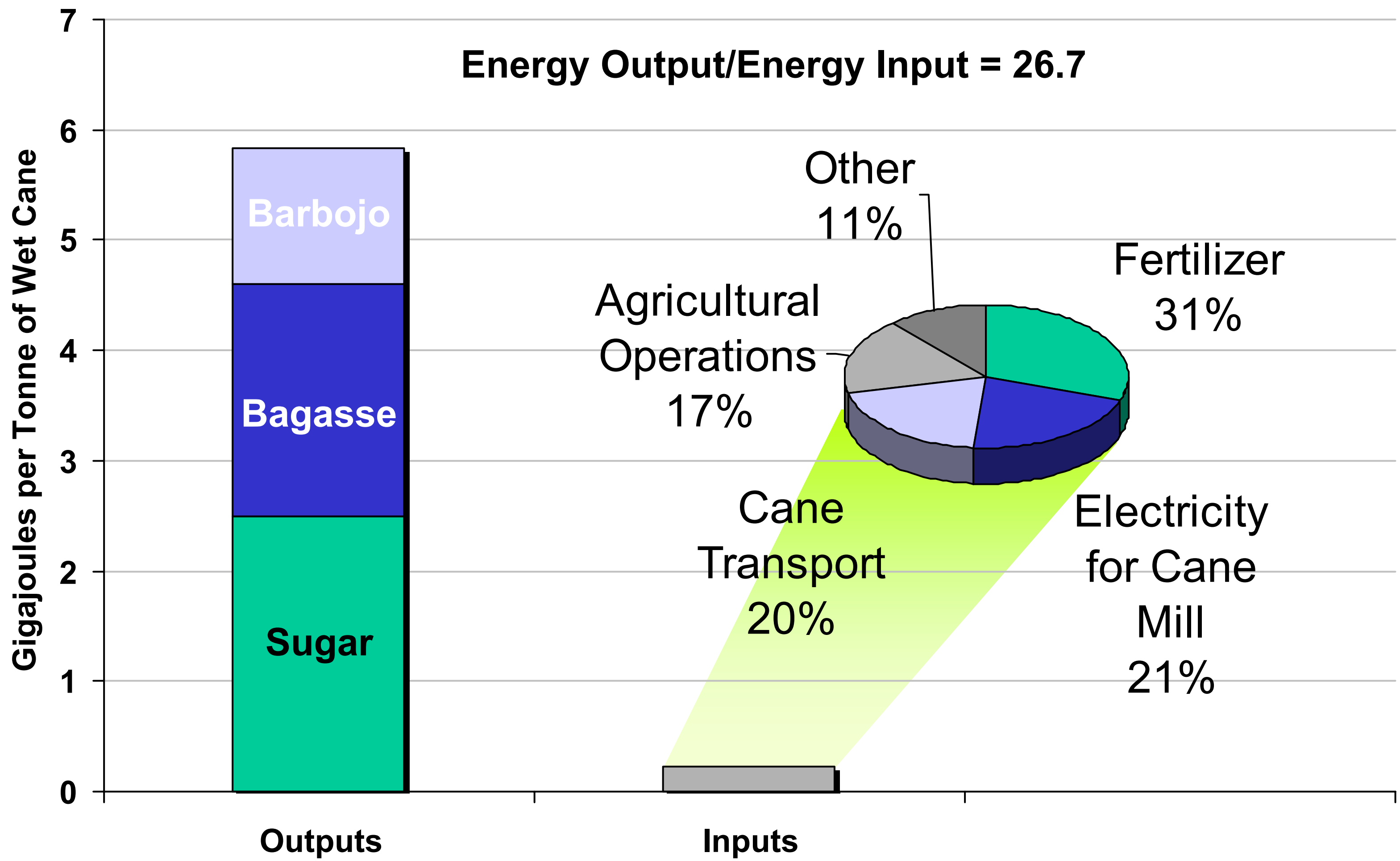
- Recoverable residues are poorly utilized at present:
  - Bagasse is converted to electricity via inefficient steam turbines
  - Barbojo is typically not recovered (*burned off in fields before harvest*)

BRAZIL HAS SHOWN THAT ETHANOL CAN COMPETE WITH GASOLINE FROM CRUDE OIL

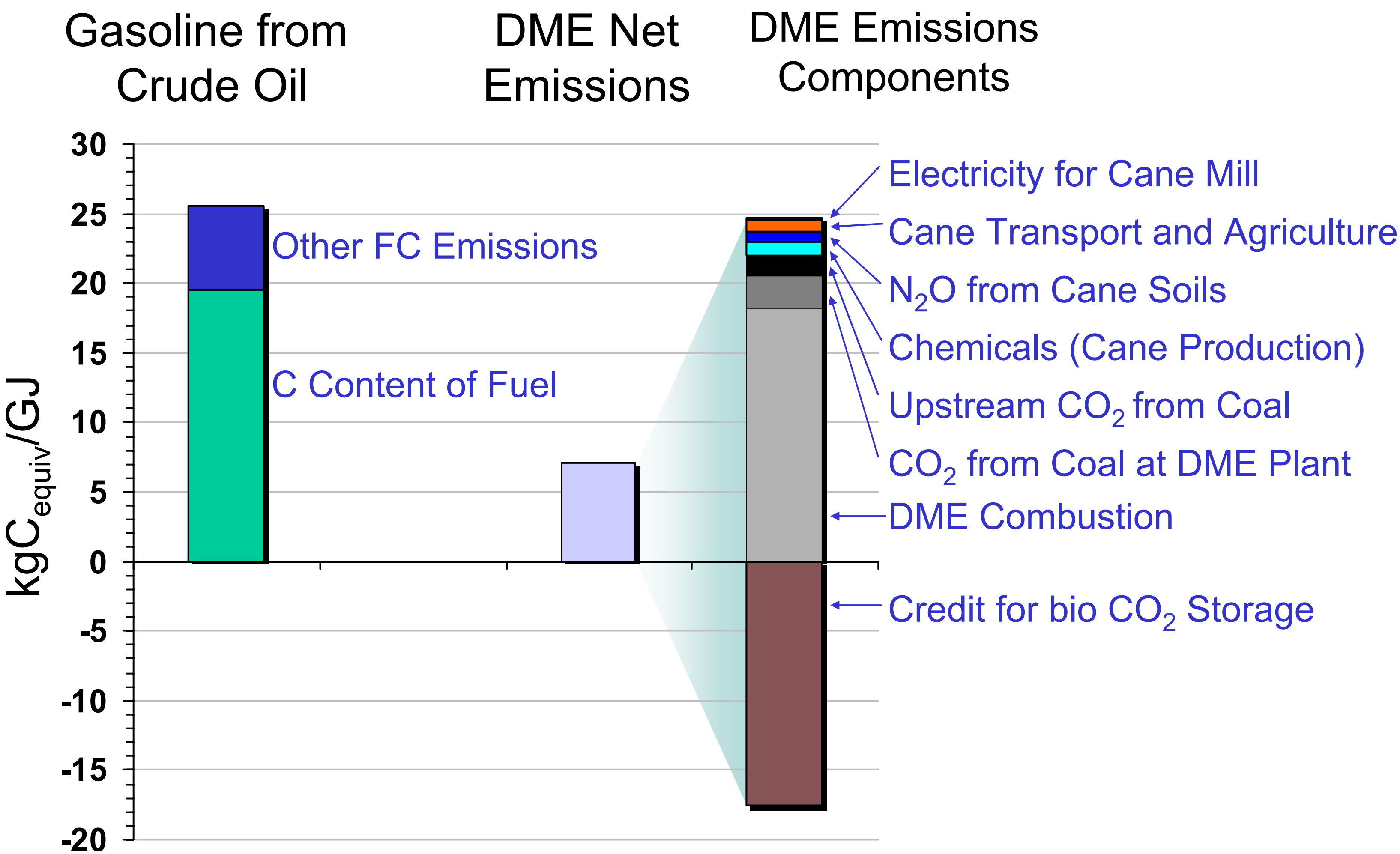


Source: J. Goldemberg, J., S.T. Coelho, P.M. Nastari, and O. Lucon, "Ethanol learning curve—the Brazilian experience," *Biomass and Bioenergy*, **26**: 301-304, 2004.

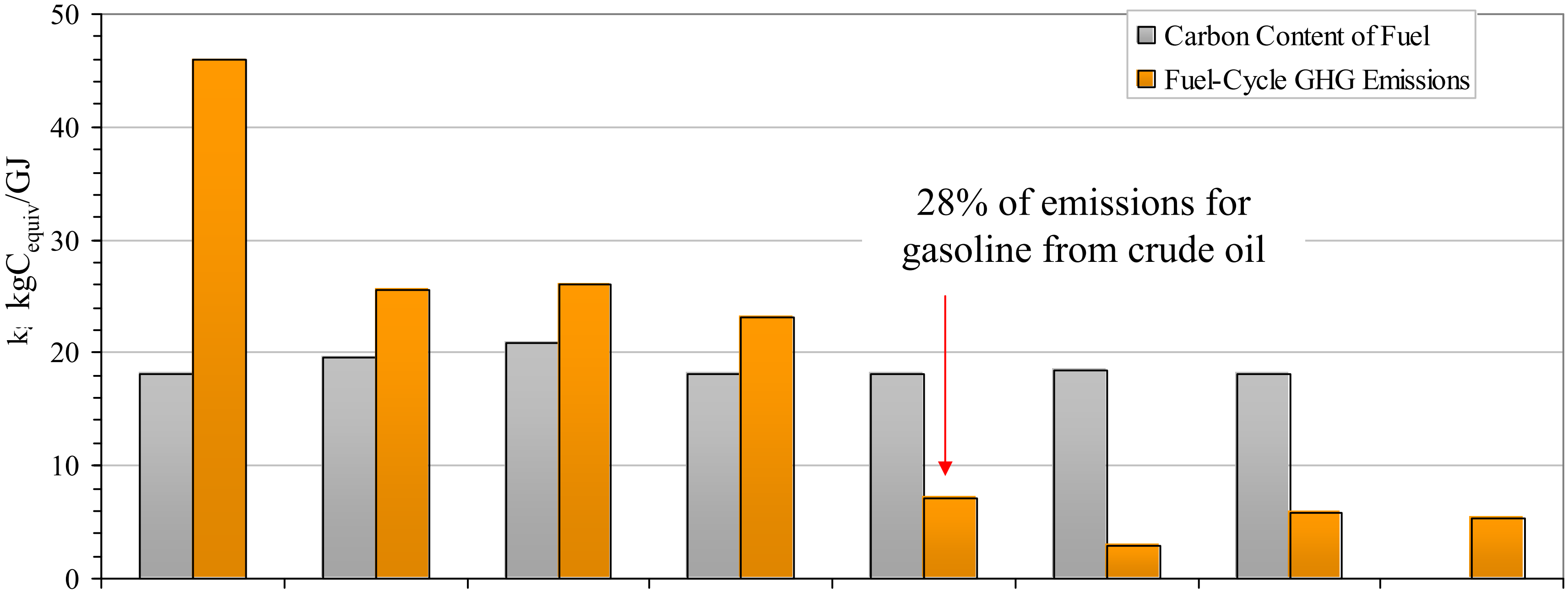
VERY ATTRACTIVE ENERGY BALANCE FOR CANE PRODUCTION



FUEL CYCLE (FC) GHG EMISSIONS FOR CRUDE-OIL-DERIVED GASOLINE, COAL/CANE RESIDUE-DERIVED DME

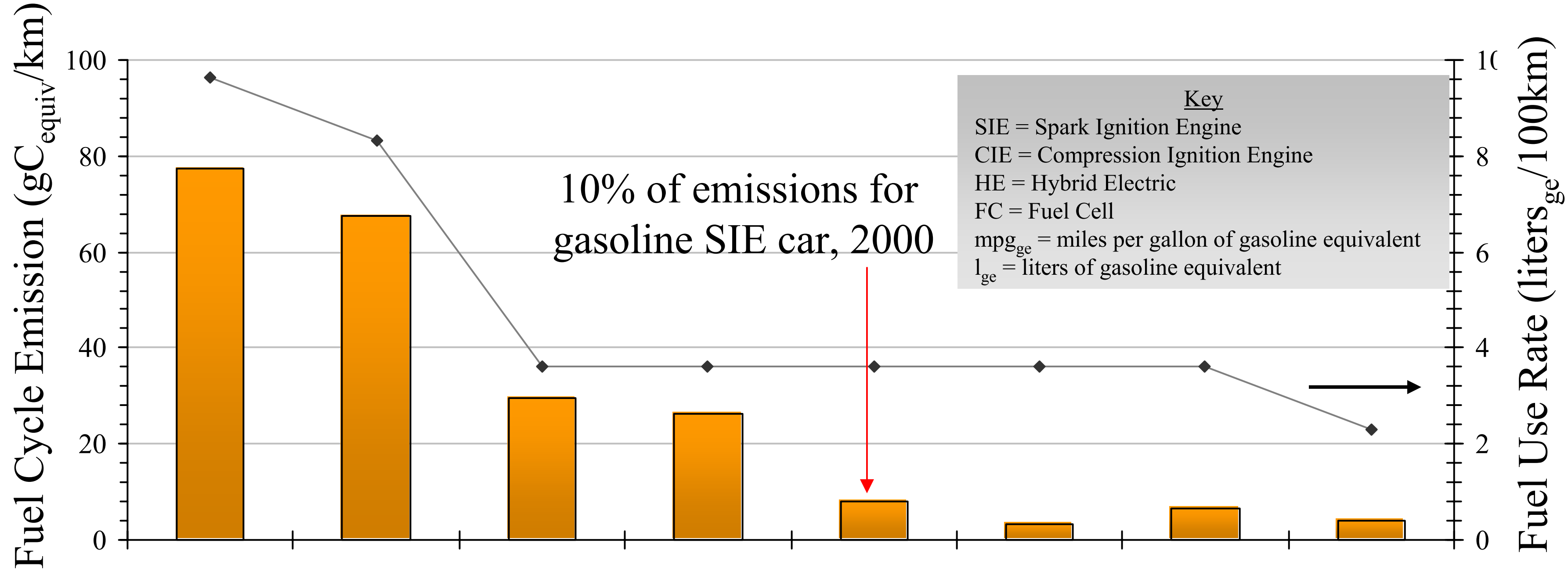


FUEL CARBON CONTENT & FUEL-CYCLE-WIDE GHG EMISSIONS FOR ALTERNATIVE FUELS/PRIMARY ENERGY SOURCES



Energy Carrier	DME	Gasoline	Diesel	DME	DME	Ethanol + DME	DME	Hydrogen
Primary Energy Source	Coal	Crude Oil	Crude Oil	Coal	Coal/Cane Residue	Cane Sugar + Coal/Cane Residue	Biomass	Coal
CO_2 Capture and Storage?	No	No	No	Yes	Yes	Yes	No	Yes

FUEL-CYCLE-WIDE GHG EMISSIONS FOR ALTERNATIVE FUELS/PRIMARY ENERGY SOURCES/AUTO ENGINES



Engine	SIE	SIE	CIE/HE	CIE/HE	CIE/HE	CIE/HE, SIE/HE	CIE/HE	FC/HE
Fuel	Gasoline	Gasoline	Diesel	DME	DME	Ethanol + DME	DME	Hydrogen
Primary Energy	Crude Oil	Crude Oil	Crude Oil	Coal	Coal/Cane Residue	Cane Sugar + Coal/Cane Residue	Biomass	Coal
Fuel Use Rate (l_{ge}/100km)	9.62[a]	8.31[b]	3.61	3.61	3.61	3.61	3.61	2.31
Fuel Economy (mpg_{ge})	24.4[a]	28.0[b]	65.2	65.2	65.2	65.2	65.2	101.7
CO_2 Capture and Storage?	No	No	No	Yes	Yes	Yes	No	Yes

[a] World Average, 2000

[b] World Average Projected for 2030, Sustainability Mobility Project

THOUGHT EXPERIMENT FOR CANE, COAL, & CARS

- Suppose that for all sugar cane currently produced on 20 million ha:
  - Bagasse + recoverable barbojo are gasified along with coal to make DME + decarbonized electricity with CO_2 capture and storage (CCS)
  - "Cane" syngas is used to make just enough H_2 to raise H_2/CO ratio in coal syngas to 1.0—the ratio needed to make DME in synthesis reactor
  - CO_2 coproducts of cane-derived H_2 & coal processing are stored underground
  - DME is used in fuel-efficient hybrid electric cars (*65mpg$_{ge}$*)
- Implications:
  - Could support 360 x 10^6 LDVs (*~ ½ world's cars*) that would otherwise consume 8.7 MMB/D of oil (*Saudi Arabia's production = 8.4 MMB/D in 2000*)
  - GHG emissions/km for DME CIE/HE cars ~ 1/10 rate for today's gasoline cars
  - 10% increase in global coal production reduction
  - CO_2 storage rate ~ 200 x 10^6 tC/y

IS BIOMASS/COAL CO-PROCESSING NECESSARY TO EXPLOIT NEGATIVE EMISSIONS POTENTIAL OF BIOMASS?

- Coprocessing offers biofuel developer several benefits:
  - Economies of scale for all feedstock processing activities
  - Economies of scale for CO_2 compressor and CO_2 transport
  - Shouldering by fossil fuel partner of major responsibility for synfuel technology development/marketing ➔ early opportunity for biofuels
- But biomass/coal co-processing might not be practical in some biomass-rich regions because of remoteness of coal supplies
- What about stand-alone biomass-H_2 plants?
  - Markets for H_2 as an energy carrier are not likely to evolve very rapidly
  - Long-distance transport of bio H_2 to coal synfuel plants/other markets costly
- But the negative emissions potential of biomass might be readily exploitable at stand-alone synfuel plants (*e.g., F-T liquids or DME*)

NEGATIVE EMISSIONS WITH BIO-SYNFUELS

- According to recent study[a]: making DME, F-T liquids from biomass involves removing nearly pure CO_2 (~ *45-50% of C in biomass*) upstream of synthesis ➔ low-cost CO_2 capture
- Possible issue—would scales be adequate to make CO_2 transport to storage cost-effective?
- DME example: CO_2 recovery rate ~ 1.2 X C content of DME ➔
  - Strong negative emissions
  - Net near zero emissions if each EJ/y of coal synfuel matched by an EJ/y of biomass synfuel, with CCS in each case
- Major C-trading opportunity for biomass-rich countries
- Coal synfuel-producing regions could meet climate mitigation obligation by promoting development of biomass synfuels with CCS in biomass-rich regions (*coal/biomass partnering w/o coprocessing*)

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[a] E. Larson, H. Jin, and F. Celik, "Thermochemical Fuels Production from Switchgrass," Princeton Environmental Institute, draft manuscript, 15 October 2004

CONCLUSIONS

- Seems feasible to make a major contribution in addressing challenges posed by the automobile—in this quarter century—via production and use of designer synfuels derived from coal and biomass with CCS
    - Major technical uncertainty is "gigascale" viability of CO_2 storage—many more "megascale" CO_2 storage demos needed…soon
    - Biomass synfuel and H_2 production must be demonstrated…a Swedish biomass DME demo now getting underway could provide platform for this
    - Also demos for coal synfuels plants with CCS…but radically new technologies not needed
- Enactment of carbon mitigation policy needed…but there seems to hope in this regard…Kyoto now in place...growing anxiousness in private sector in US to evolve beyond "voluntarism"
- Institutional and cultural challenges may be more daunting than technological challenges:
    - Overcoming widespread ill feelings about coal synfuels—costly synfuels failures of late 1970s-early 1980s
    - Political will to enact ambitious automotive efficiency improvement policy?
    - Coalition-building challenge for proposed strategy—across multiple industries and via international collaborations (*e.g., Brazil and Australia*)


BIG COAL
GRO MOR
CARS R US
BIG OIL